

Uranium isotopic disequilibrium for groundwater classification: first results on complexe terminal and continental intercalaire aquifers in Southern Tunisia

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Abstract A fractionation of uranium (U) series into parent–daughter pairs ^{234}U and ^{238}U always occurs in natural waters, and the disequilibria between these is commonly used as a tracer of groundwater flow. We report here an interpretation of the U-content and U isotope disequilibria in groundwater sampled from the deep Complexe Terminal and Continental Intercalaire aquifers of southern Tunisia. Variations in both the contents of these isotopes (0.006–2.4 ppb) and $^{234}\text{U}/^{238}\text{U}$ activity ratios (ARs) (1.7–15.4) were observed. The data could be plotted in two distinct fields of reciprocal U concentration versus $^{234}\text{U}/^{238}\text{U}$ AR according to groundwater flow and regional bedrock differences. An initial assessment aimed at verifying whether the results of this investigation support those of previous hydrogeological and isotope studies, thereby suggesting that the disequilibrium between U isotopes in groundwater may represent a useful tool for hydrogeological investigations of deep and fossil groundwater. In addition, the disequilibrium can be used for quantifying the recharge or mixing rates between different formations with the aim of delineating the preferential outflow pattern or determining residence times of waters.

Keywords Tunisia · Uranium isotopes · $^{234}\text{U}/^{238}\text{U}$ AR · Water tracing

Introduction

The abundance of the two uranium (U) isotopes, ^{234}U and ^{238}U , has been used extensively to characterize groundwater. In natural water, the ratio of ^{234}U to ^{238}U is almost always found to differ significantly from its equilibrium value. This isotopic disequilibrium results from geochemical sorting or differentiation processes that may be physical as well as chemical, and isotopic as well as elemental (Osmond and Cowart 1992). Aquifers where groundwater and aquifer rock are in close contact are favorite systems for both chemical and physical differentiation, especially when water and minerals are strongly mixed; consequently, the rock–water ratio, surface area and residence time have large values. These conditions are often observed in deep, fossil groundwater.

There are relatively few cases in which disequilibrium phenomena have been applied to resolve hydrogeological problems. However, in several studies (Osmond and Cowart 1976; Meyer 1989; Banner et al. 1991; Roback et al. 2001; Dabous and Osmond 2001; Suksi et al. 2001), the use of U series disequilibria in describing aquifer processes has been successful. This approach can be used to classify aquifers (steady-state, augmenting or decaying systems) or to identify the sources and mixing proportions of aquifer water. The dating of groundwater by disequilibrium techniques is challenging. Radiometric age determination in any case is possible only if three conditions are present: the age of the system being dated is of the same magnitude as the lifetime of the radionuclide used, the initial state of disequilibrium is known and the radionuclide content of the system has not changed other than by radioactive decay. In groundwater, the closed system requirement is very difficult to verify, and the most limiting problem remains the estimation of initial radionuclide contents.

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Theory

Normally, the fractionation of heavy nuclides in chemical processes is negligible, particularly in natural environments. However, in the half century that has past since the first studies were carried out on the natural radioactivity of geological elements (Cherdynstev 1955; Thurber 1962; Gascoyne 1992), the disequilibrium between ^{238}U and ^{234}U in rocks and their leached solutions in natural water has been found to be the rule rather than the exception. $^{234}\text{U}/^{238}\text{U}$ activity ratios (ARs) in waters have been observed to vary from 0.5 to 40 (Osmond and Cowart 1992), while U contents range from 0.01 to 5 $\mu\text{g/l}$ in surface water (Gascoyne 1992) and from 0.1 to 50 $\mu\text{g/l}$ up to 10,000 $\mu\text{g/l}$ in groundwater (Osmond and Cowart 1992). The AR of seawater has been found to be constant at 1.14, which is equivalent to a U content of 3.3 $\mu\text{g/l}$ (Ku et al. 1977; Chen et al. 1986). Uranium dissolved in groundwater commonly forms complex ions, depending on such geochemical conditions as pH, Eh and the presence of other dissolved ions (Langmuir 1978). The mobility of dissolved U in natural waters is affected by processes such as adsorption or desorption of U ions and precipitation or dissolution of U-bearing minerals. One of the most common methods to characterize a groundwater aquifer is to diagram the $^{234}\text{U}/^{238}\text{U}$ AR against the reciprocal of the U-content. This approach can be used to classify aquifers in terms of U-content – oxidized aquifer on “normal” U-content strata (values between 1 and 10 ppb), oxidized aquifer on enhanced U-content strata (values higher than 10 ppb) and reduced aquifer on low U-content strata (values lower than 1 ppb) – and in terms of $^{234}\text{U}/^{238}\text{U}$ ARs – “normal” world-wide groundwater (values between 1 and 2), possibility of formation processes (values higher than 2) or remobilization (values lower than 1). In the present study, data on dissolved U and the isotopic AR in groundwater samples from Complexe Terminal (CT) and Continental Intercalaire (CI) aquifers in southern Tunisia were used to evaluate the applicability of the model in the area.

Study area

The survey zone is located on the Djérid and Nefzaoua basin in southwestern Tunisia (Fig. 1). The study area is limited on the north by the Gafsa-Metlaoui chain of mountains (900–1100 m a.s.l.), on the west by the Tuniso-Algerian frontier, on the south by the Grand Erg Oriental and on the east by the ElHamma fault and the mountain chain of the Dahar (500–700 m a.s.l.) (Mamou 1990). This zone is characterized by an arid climate. Annual precipitation averages less than 100 mm, and precipitations are marked by a scattered spatial and temporal distribution.

The mean annual temperature is of the order of 21°C, while the evaporation rate is more than 1700 mm/year.

The CI and CT aquifers lie under the entire area of the Lower Sahara. The CI aquifer, lying in the continental formations of the lower Cretaceous period, is one of biggest aquifers in the world and has a surface area of 600,000 km². The CT aquifer, with a surface area of 350,000 km², is found in the sandy and calcareous formations of the upper Cretaceous and Tertiary formations. These two aquifers are considered to contain essentially fossil groundwater resources. Several studies and research projects have been carried out on this area since the 1960s (ERESS 1972; Gonfiantini et al. 1974; Aranyosy and Mamou 1986; Mamou 1990; Edmonds et al. 1997; Gries 2000) and, consequently, the hydrogeological, hydrochemical and isotopic characteristics of these aquifers are well known.

In the present study, 35 groundwater samples, collected from the CI and CT aquifers over the Djérid and Nefzaoua basins (southern Tunisia), were subjected to standard analytical procedures for determination of the U content and AR using alpha spectrometry techniques (Chakroun 2003). The sampling was performed along paleoshorelines of Chott Fejej and Chott Djérid (Fig. 1). As some of the analyses were unsuccessful because of detection limitations of the technique, only 20 samples were ultimately plotted samples.

Hydrogeology

This study concerned two of the main aquifers of southern Tunisia (Fig. 2).

- The Continental Intercalaire aquifer is located in the Lower Cretaceous continental formations (Neocomian, Barremian, Aptian and Albian) and underlies all the of the Sahara. The geological formations constituting this aquifer present large variations of facies and thickness from the zone of the Chotts to the Sahara platform. Sedimentation changes in continental fluvio-deltaic deposits produced detrital levels alternating with clayey silt intercalations and, frequently, gypsum intercalations. The water-bearing bed of the CI aquifer is bounded by the Neocomian at the basis and the Albian at the top (Mamou 1990). These formations are between 1550 and 2300 m deep. The groundwater system consists of two great sectors, a western zone where the main flow path is directed towards the southwest, and an eastern zone where the main flow path is to the northeast. This latter sector, the Erg Oriental Basin, extends from Algeria to Tunisia; its natural discharge is located on Gulf of Gabès. According to piezometric

Fig. 1 Geographical setting of sampled boreholes for the Continental Intercalaire (CI) and Complexe Terminal (CT) aquifers, southern Tunisia

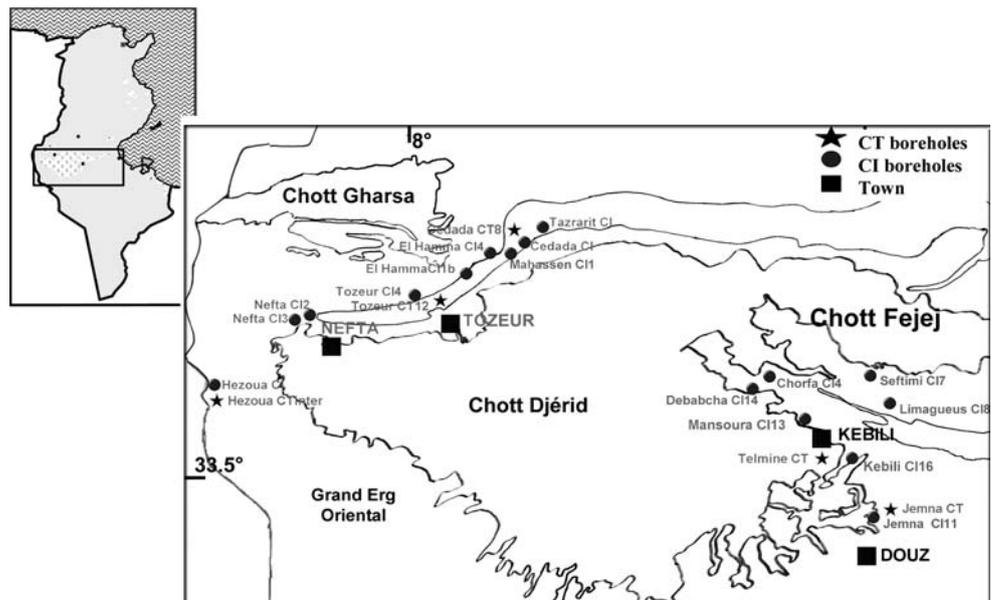
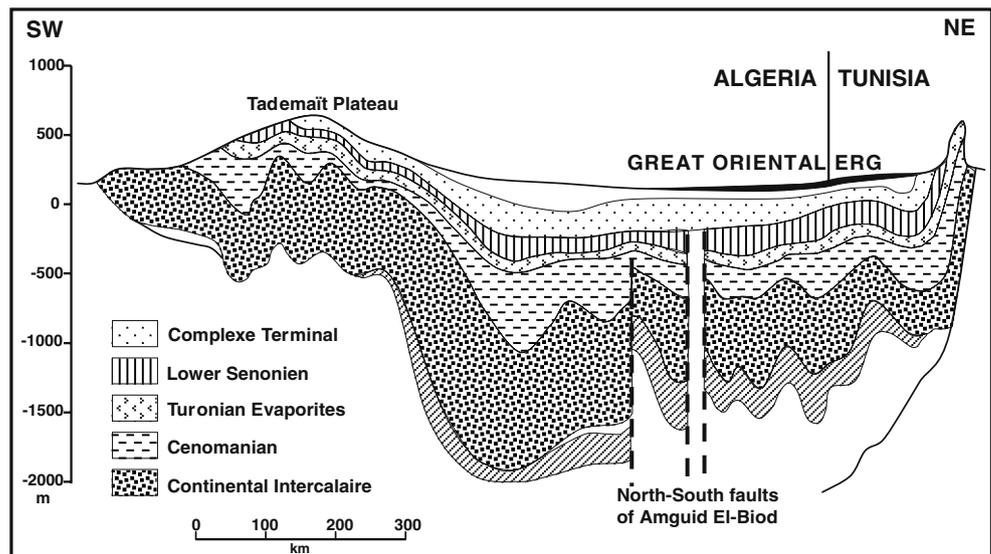


Fig. 2 Schematic section through the CI aquifer and the CT aquifer in Tunisia and Algeria (from Edmunds et al. 1997)



lines and spatial distribution of salinity, the recharge area is located on the Tunisian Dahar in southeastern Tunisia (ERESS 1972; Mamou 1990).

- The Complexe Terminal aquifer formed in the Upper Cretaceous limestone of the Senonian in Nefzaoua basin and consists of the sandy tertiary formations with thin clayey intercalations of the lower Pontien in the Djérid basin (Fig. 2). The CT aquifer overlies the CI aquifer. The depth of the latter aquifer varies between 70 and 250 m in the Nefzaoua region and between 80 and 700 m in the Djerid region. The main outflow direction is south–southeast to north–northwest. The north–northwest discharge zone contains artesian springs.

First results on CI and CT aquifers

The level of dissolved U in the groundwater from the CI aquifer varied greatly (Table 1) as did the U-content and AR values insamples from all of the classification categories. Uranium concentrations and AR values of the groundwater from the two aquifers are classified in Fig. 3 by geographic and lithostratigraphic environment.

- Groundwater sampled from the CT aquifer was determined to have a U-content that ranged from 1.35 to 2.40 ppb with “normal” AR values ranging around 2 (Bonotto 1999). The data are quite homogeneous for both the Nefzaoua and Djerid regions. This aquifer has

the highest U-content values, indicating an oxidizing environment for an unconfined aquifer.

- Groundwater sampled from the CI aquifer was found to have a low U-content (less than 0.5 ppb), while the AR values are greater than 2, ranging up to 15. The two regions of *Djerid* and *Nefzaoua* show great differences that can be related not only to lithostratigraphic formations but also to different origin of groundwater. For the Nefzaoua region, it can be assumed that the deep groundwater originated from the Dahar mountain recharge area; therefore, it is considerably younger than the CI groundwater in the Djerid area.

To interpret these data, theoretical knowledge and anterior case studies (Osmond and Cowart 1992) were used. Diagrams relating reciprocal U-content versus the $^{234}\text{U}/^{238}\text{U}$ AR were plotted to highlight the different processes in the aquifers (Osmond and Cowart 2000). $^{234}\text{U}/^{238}\text{U}$ ARs plotted against reciprocal U concentrations on the mixing diagrams typically exhibit a linear trend extending from the lower left (low AR with high concentrations) to upper right (high AR with low concentrations). This can be interpreted as mixing lines (Dabous and Osmond 2001); at one end is very dilute aquifer water, which has experienced little leaching of U (upper right), and at the other end member is the concentrated leachate of the host rock (lower left). The dispersion of points between these two end members indicates water with various mixture ratios. The trend line is defined by two parameters: the y-intercept, which is the $^{234}\text{U}/^{238}\text{U}$ AR of the U being leached from the host rock, and the slope of the trend line, which is the ^{234}U -excess per kilogram (U-equivalent ppb) and is characteristic of the pre-leach water. The unit for ^{234}U -excess is U-equivalent parts per billion, which is the concentration in micrograms per kilogram of an equilibrated amount of ^{238}U (^{234}U activity per mass of water) (Dabous and Osmond 2001).

The interpretation of the data is supported by the hydrogeological and hydrochemical characteristics of aquifers (Table 2).

Table 1 Results from an analysis of 20 groundwater samples from the Continental Intercalaire (CI) and Complexe Terminal (CT) aquifers

	U-content (ppb)		$^{234}\text{U}/^{238}\text{U}$ activity ratio	
	Minimum	Maximum	Minimum	Maximum
CI aquifer	0.006	0.568	3.188	15.376
CT aquifer	1.347	2.398	1.669	2.525

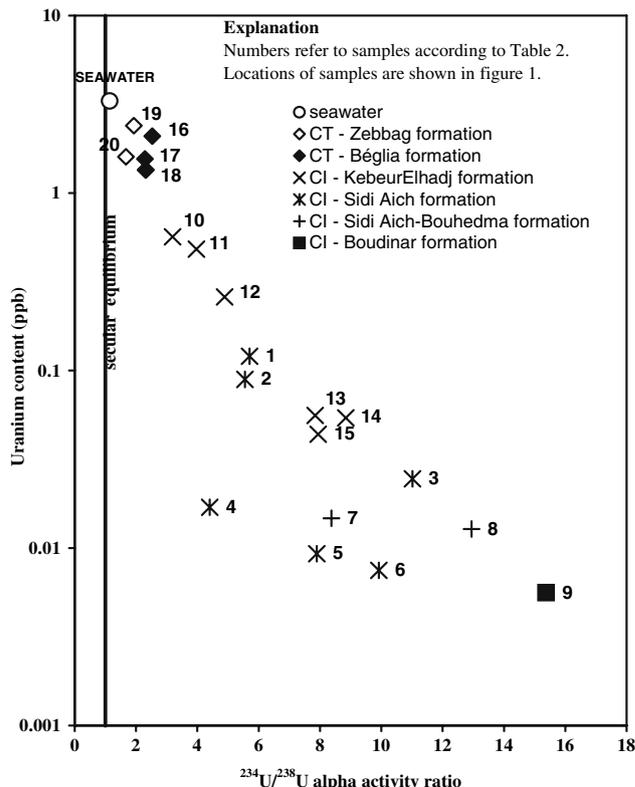


Fig. 3 Scattergram showing U-content and the $^{234}\text{U}/^{238}\text{U}$ activity ratio (AR) in the groundwater samples (1–20). Seawater is known to have essentially a constant uranium content of 3.3 ppb and an activity ratio of 1.14 (Ku et al. 1977; Chen et al. 1986) and is plotted here as reference point

Discussion of results for CT aquifer

Only five points represent this aquifer, so even if a leaching trend does seem apparent on the diagram of reciprocal U-content versus $^{234}\text{U}/^{238}\text{U}$ AR, it was not extrapolated. However, to place these data in the global setting of the aquifer, some relationships between U isotopic variation and other geochemical data were referenced. U-contents are not significantly dependant on depth, but $^{234}\text{U}/^{238}\text{U}$ ARs show different trends between the two regions (Fig. 4).

In Djérid, where samples were collected from the Bégia formation, which is constituted of Pontien sands (samples 16, 17 and 18); the variation in uranium contents and ARs does not show a clear tendency, although $^{234}\text{U}/^{238}\text{U}$ ARs do decrease with increasing depth. These samples were collected along a previously established line perpendicular to the aquifer flow path (Fig. 5), so ^{234}U precipitation along a flow path can be excluded as a possible explanation of the data. A dilution process and subsequent mixing of groundwater, with some samples experiencing more dilution than others, may explain this trend. However, due to the limited number of sampling points and the incomplete

Table 2 Data for the CT and CI aquifers (this study; Gries 2000)^a

Number of site	Name	Formation ^b	U (ppb)	1/U (kg/μg)	²³⁴ U/ ²³⁸ U	Depth (m)	RS (g/l)	Temperature (°C)
Continental Intercalaire – Djérid region								
1	ElHammaCI1Bis	SA	0.120	8.31	5.70	1,550	2.75	69.8
2	MahacenCI1	SA	0.089	11.21	5.55	2,557	3.00	62.9
3	CedadaCI	SA	0.025	40.65	11.02	2,371	2.26	50
4	TazraritCI	SA	0.017	58.82	4.40	2,186	4.12	52.4
5	TozeurCI4	SA	0.009	107.53	7.90	1,981	4.88	54.4
6	HazouaCI	SA	0.008	133.33	9.92	2,059	1.80	59.1
7	ElHammaCI4	SA-BH	0.015	68.03	8.37	1,475	2.72	69.5
8	NeftaCI3	SA-BH	0.013	78.13	12.94	2,190	2.82	57.9
9	NeftaCI2	BD	0.006	178.57	15.38	2,584	2.67	66.7
Continental Intercalaire – Nefzaoua region								
10	SeftimiCI7	KH	0.568	1.76	3.19	1,786	2.44	67.6
11	KebiliCI6	KH	0.483	2.07	3.97	2,774	2.22	63.7
12	LimagueusCI8	KH	0.259	3.86	4.89	1,730	2.42	67
13	ChorfaCI4	KH	0.056	17.92	7.84	2,190	2.21	59.5
14	DebabchaCI4	KH	0.054	18.48	8.84	2,295	2.03	68.1
15	MansouraCI3	KH	0.044	22.83	7.94	1,430	2.24	63.8
Complexe Terminal – Djerid region								
16	HazouaCT1inter	Bg	2.099	0.48	2.53	528	2.62	28.8
17	CedadaCT8	Bg	1.347	0.74	2.31	590	1.6	33.6
18	TozeurCT2	Bg	1.556	0.64	2.29	622	1.83	29.6
Complexe Terminal – Nefzaoua region								
19	TelmineCT	Zg	2.398	0.42	1.93	201	2.21	23
20	JemnaCT	Zg	1.600	0.63	1.67	118	1.3	20

^a Lithostratigraphy (Edmunds et al. 1997)

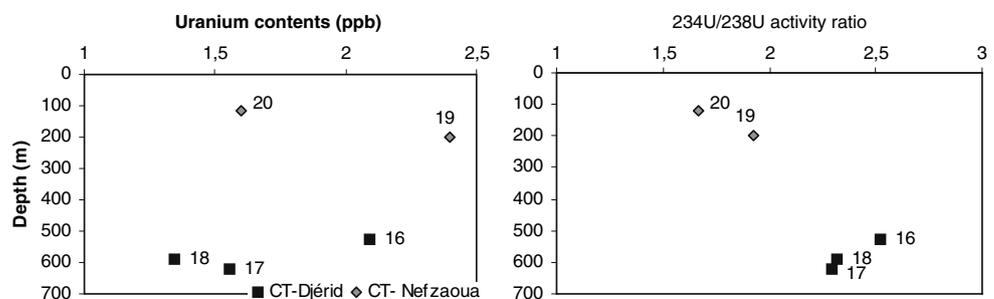
^b SA, Sidi Aich (Barremian-Aptian): friable white and fine grained sands; BH, Bou Hedma (Barremian-Bedoulian): a calcareous marl formation; KH, Kebeur El Hadj (Neocomian): an alternative sequence of detrital and clayey sediments; BD, Bou Dinar (Barremian): an alternative sequence of sandy and clayey sediments; Zg, Zebbag (Cenomanien-Turonien): limestone and dolomite; Bg, Beglia (Neogene): an alternative sequence of sands and clayey levels

data set on the U isotopic characteristics of the recharge area, we did not calculate the relative mixing rate. Further investigations are planned.

In the Nefzaoua region, samples were collected from the Zebbag formation, which consists of Cenomanien limestone (samples 19 and 20). Increased U-content and ARs occur according to the local south–north flow of the

aquifer in this zone (Mamou 1990). This increase is also observed for depth, temperature and mineralization. Since the aquifer lies in carbonates, a possible hypothesis is a preferential dissolution of ²³⁴U from the matrix rock. On the other hand, ²³⁴U/²³⁸U ARs do increase with depth. The two sampling points, however, do not provide sufficient information for a meaningful interpretation to be

Fig. 4 Uranium isotopic data versus depth of groundwater sampled in CT aquifer. The numbers refer to sites given in Table 2



made, and further investigations are necessary (in preparation).

Discussion of results for CI aquifer

The results of uranium isotopic analysis for CI aquifer are plotted in Fig. 6. Two groups of samples can be distinguished along the two trends. Although variations in concentrations and activity ratios can be observed among groundwater samples from the same region, these two mixing lines are consistent in terms of the complexity of the system.

Group 1 samples (1, 2, 4, 5, 6, 7, 8 and 9) collected from the Djérid zone display a linear pattern from the lower left to the upper right. Along this straight line, U-content increases, while $^{234}\text{U}/^{238}\text{U}$ AR decreases. It is a first leaching line: preferential ^{234}U dissolution is enhanced by a weak hydraulic gradient that facilitates the water–rock interaction. The first end member (upper right), which is expected to be very dilute aquifer water that has experienced very little leaching of U, corresponds in this area to water sampled from the oldest formation (sample 9; Table 2), as observed by Dabous and Osmond (2001) for Nubian aquifer (Egypt). The second end member (lower left), which is expected to be a concentrated leachate of the host rock, corresponds to groundwater sampled at point 1 and point 2 (Table 2). However, it cannot be considered to be the origin of the aquifer groundwater because the recharge zone is known to be in Algeria. However, it is noticeable that these two points correspond to water with the highest temperature (69° and 63°C, respectively), which probably enhances the leaching of U from host rock. For the Djérid area, ^{234}U -excess is about 0.045 (U-equivalent ppb) and the AR of the host rock U is 5.58. The movement of plotted points around the trend line can be explained by different mixing ratios between the two end members. In support of this, two samples [El Hamma CI4 (7) and Nefta CI2 (9)] collected from boreholes extended over intervals that covered two different formations of the CI aquifer.

Group 2 samples (10, 11, 12, 13, 14, 15) collected from the Nefzaoua zone (Kebeur El Hadj formation) display a linear pattern from the lower left to the upper right. The same process as that mentioned above is observed between an end member characterized by a low U concentration with a high AR and a second end member with high U concentration and low AR. Here, however, the higher U concentrations (up to 0.6 ppb) are probably enhanced by the effect of high temperatures (around 65°C) of the Kebeur el Hadj limestones, which are commonly more enriched in U-content, and by the greater hydraulic gradients (Fig. 7), which make water–rock exchanges more efficient than in Djérid zone. For the Nefzaoua area,

^{234}U -excess is about 0.24 (U-equivalent ppb) and the AR of the host rock U is 3.47.

Conclusion

The aim of this study was to investigate the potential advantages of using U isotopic variation for characterizing one of the greatest fossil groundwater resources in the world. This groundwater resource lies under the entire expanse of the Sahara, from the Atlas Chain in Morocco (west) to the North African coast of the Mediterranean sea in Tunisia (east) and southwards to the Tassili of the Hoggar. Our initial objective, which was to use the long-life radionuclides ^{234}U and ^{238}U for evaluating the residence times (age) of this groundwater, was achieved in part: the data obtained on the U isotopes in the groundwater from the two main aquifers of southern Tunisia are in good agreement with data from hydrogeology and with other geochemical and isotope studies.

The upper Complexe Terminal aquifer has a restricted range of U-contents (1.35–2.4 ppb) associated with relatively low $^{234}\text{U}/^{238}\text{U}$ ARs (1.7–2.5), both of which are characteristic of normal groundwater worldwide. The variations in U isotopes in terms of the hydrogeologic setting of the aquifer confirm that this aquifer is unconfined and suggest that the main process affecting U isotope patterns is groundwater mixing. However, the number of sampled points was limited and further investigations are needed.

The Continental Intercalaire aquifer has a wide range – but lower values – of U (0.006–0.57 ppb) associated with relatively high $^{234}\text{U}/^{238}\text{U}$ ARs (3.2–15.4). High $^{234}\text{U}/^{238}\text{U}$ ARs (east) have been reported for deep groundwater and have been explained either by a long history of high surface area interaction between water of low U solubility and an aquifer rock with relatively higher concentrations of U (factor of 1000) (Kronfeld et al. 1975) or by elevated temperatures that may enhance rock–water isotopic re-equilibration (Kramer and Kharaka 1986). Consequently, high $^{234}\text{U}/^{238}\text{U}$ ARs are often observed in large aquifers with steady long-term flow systems, such as that of the CI aquifer and are characteristic of confined fossil groundwater. Variations in U isotopes in terms of the hydrogeologic setting suggest that the probable process taking place in this aquifer is a water–rock interaction, primarily in the Nefzaoua zone (southern side of the aquifer). Here, the water-bearing limestones have a low permeability and a low flow gradient, which allows longer contact between the fluid and the solid. Thus, even if data are not available on U concentrations in the aquifer rocks, CI groundwater is known to have a long residence time with a greater opportunity for ^{234}U preferential dissolution. In the same

Fig. 5 Piezometric levels of the CT aquifer (July 2002)

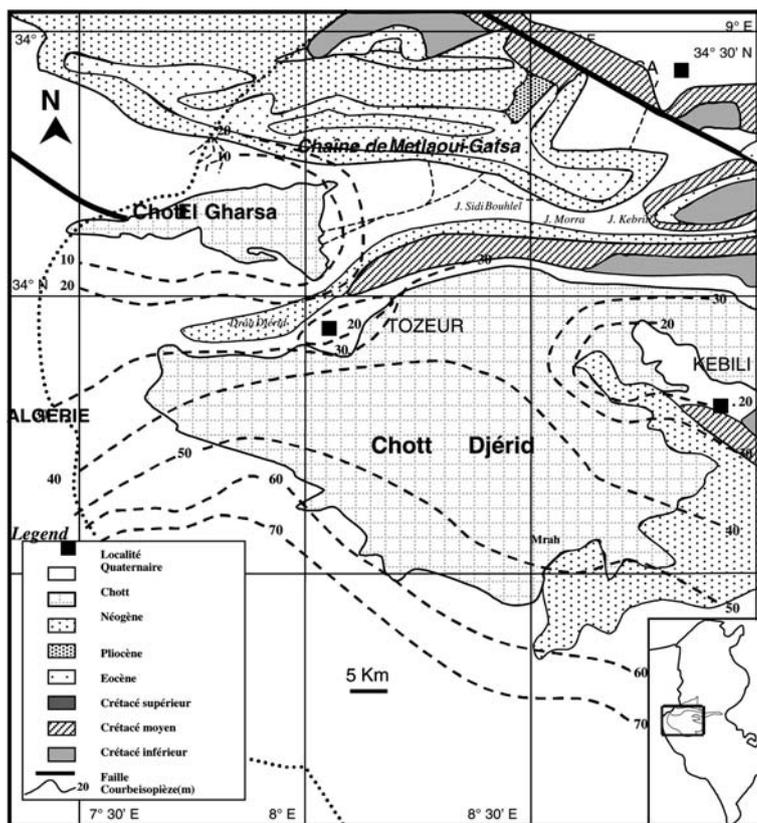
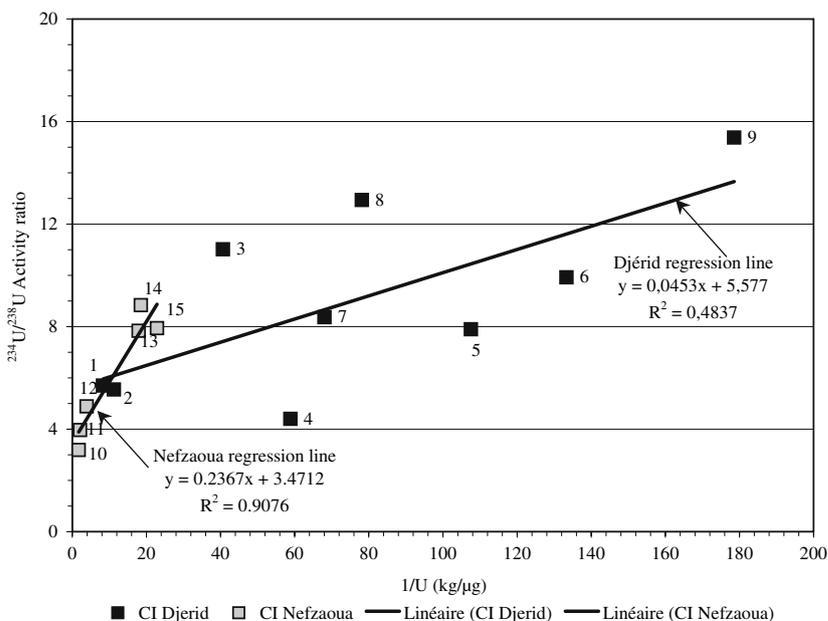


Fig. 6 Reciprocal of U-content (kg/μg) versus the $^{234}\text{U}/^{238}\text{U}$ AR for the CI aquifer. The numbers refer to sites presented in Table 2

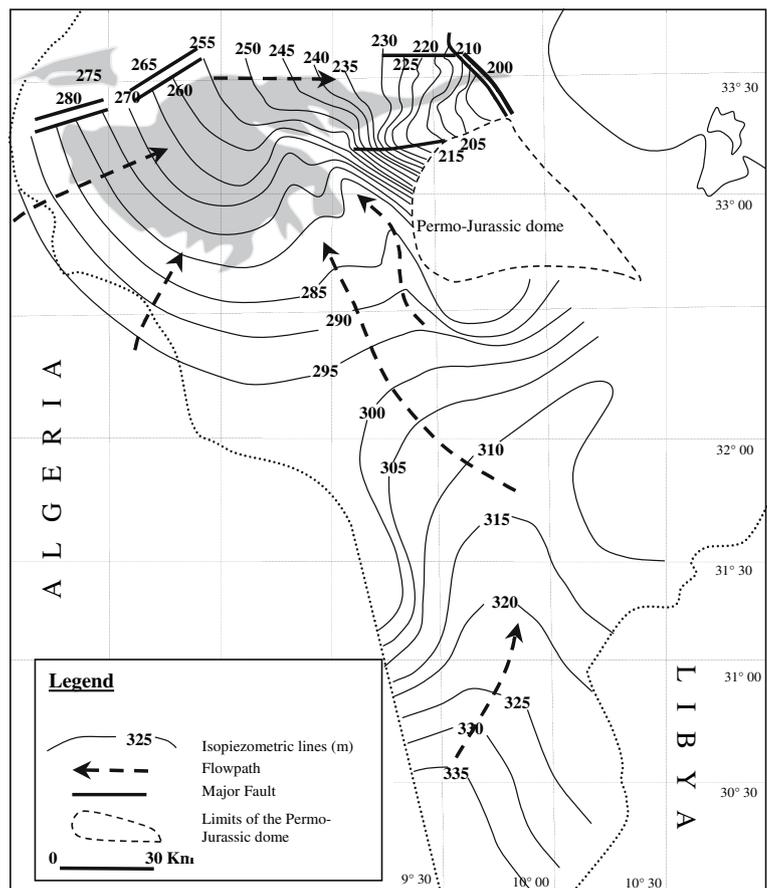


manner, high temperatures of CI groundwater may affect the values of AR by enhancing carbonate solubility.

The most important finding of this study is the high U-content and low AR found at all CT sampling sites and the fact that the formation of U isotopes in the unconfined aquifer occurs under oxidizing conditions. However, the

low U-content and high AR at the CI sampling sites are in agreement with results of previous studies and indicate a confined fossil aquifer. The differences between the two Djerid and Nefzaoua areas as well as between the different sites in a given area can be attributed to local differences in the parameters governing the U isotope composition of the

Fig. 7 Piezometric mapping of the CI aquifer (from OSS 2003)



groundwater, such as the U-content of the rock material, the properties (e.g. permeability) of the aquifer rocks and leaching rate of the two U isotopes.

References

- Aranyossy JF, Mamou A (1986) Apport des techniques nucléaires à l'étude des aquifères du Sud tunisien. Projet RAF/8/007. IAEA, Vienna
- Banner LJ, Wasserburg GJ, Chen JH, Humphrey JD (1991) Uranium series evidence on diagenesis and hydrology in Pleistocene carbonates of Barbados, West Indies. *Earth Planet Sci Lett* 107:129–137
- Bonotto DM (1999) Applicability of the uranium isotopic model as a prospecting technique in Guarany aquifer, South America. In: 9th Annual VM Goldschmidt Conf, abstr. 7021, LPI contribution no. 971. Lunar and Planetary Institute, Houston
- Chakroun I (2003) Utilisation des isotopes de l'uranium pour la caractérisation des aquifères profonds anciens. DEA Géologie, Faculty of Sciences, Sfax, Tunisia
- Chen JH, Edwards RL, Wasserburg GJ (1986) ^{238}U , ^{234}U and ^{232}Th in seawater. *Earth Planet Sci Lett* 80:241–251
- Cherdyntsev VV (1955) Uranium series disequilibrium dating In: Trans. 3rd Sess. Commission for determining the absolute Age of Geological Formations. Akad Nauk SSSR 175–182
- Dabous A, Osmond JC (2001) Uranium isotopic study of artesian and pluvial contributions to the Nubian aquifer, Western Desert, Egypt. *J Hydrol* 242: 242–253
- Edmunds WM, Shand P, Guendouz AH, Moulla AS, Mamou A, Zouari K (1997) Recharge characteristics and groundwater quality of the Grand Erg Oriental basin. In: Avicennes, technical report WD/97/46R, hydrogeology series. British Geological Survey, Keyworth, UK
- ERESS (1972) Etude des ressources en eau du Sahara Septentrional. UNESCO, Paris
- Gascoyne M (1992) Geochemistry of the actinides and their daughters, Chap 2. In: Ivanovich M, Harmon RS (eds) Uranium-series disequilibrium; applications to earth, marine, and environmental sciences. Clarendon Press, Oxford, pp 34–61
- Gonfiantini R, Conrad G, Fontes JC, Sauzy G, Payne BR (1974) Etude isotopique de la nappe du Continental Intercalaire et ses relations avec les autres nappes du Sahara Septentrional, IAEA-SM-182/25 In: Isotope techniques in groundwater hydrology, vol I. IAEA, Vienna, pp 227–241
- Gries S (2000) Etude isotopique et géochimique des nappes profondes au Sahara-Sahel – Implications pour la gestion des ressources en eau et les reconstitutions paléoclimatiques. PhD thesis, University of Paris XI, Faculty of Sciences Orsay, Paris
- Kramer TF, Kharaka YK (1986) Uranium geochemistry in US Gulf coast geopressured-geothermal system. *Geochim Cosmochim Acta* 50:1233–1238
- Kronfeld J, Dradsztan E, Müller HW, Radin J, Yaniv A, Zach R (1975) Excess ^{234}U : an aging effect in confined water. *Earth Planet Sci Lett* 27:189–196
- Ku TL, Knauss KG, Mathieu GG (1977) Uranium in open ocean: concentration and isotopic composition. *Deep Sea Res* 24:1005–1007

- Langmuir D (1978) Uranium solution–mineral equilibria at low temperatures with applications to sedimentary ore deposits. *Geochim Cosmochim Acta* 42:547–569
- Mamou A (1990) Caractéristiques, Evaluation, Gestion des ressources en eau du Sud Tunisien. PhD thesis, University of Paris South, Paris
- Meyer FW (1989) Groundwater movement in the Floridan Aquifer System in southern Florida: groundwater movement based on natural isotopes as tracers. In: US geological survey professional paper 1403-G: hydrogeology, groundwater movement and subsurface storage in the Floridan Aquifer system in southern Florida. US Geological Survey, USA
- Osmond KJ, Cowart JB (1976) The theory and uses of natural uranium isotope variations in hydrogeology. *Atomic Energy Rev* 144:621–679
- Osmond JK, Cowart JB (1992) Groundwater. In: Ivanovich M, Harmon R (eds) *Uranium series disequilibrium: applications to environmental problems*, Oxford University Press, Oxford, pp 290–323
- Osmond JK, Cowart JB (2000) U-series nuclides as tracers in groundwater hydrology. In: Cook PG, Herczeg AL (eds) *Environmental tracers in subsurface hydrology*. Kluwer, Boston, pp 145–174
- Oss (2003) *Système aquifère du Sahara Septentrional Une conscience de bassin. Volume II: Hydrogéologie*. Observatoire du Sahara et du Sahel, pp 322
- Roback RC, Johnson TM, McLing TL, Murrell MT, Luo S, Ku TL (2001) Uranium isotopic evidence for groundwater chemical evolution and flow patterns in the eastern Snake River Plain aquifer Idaho. *Geological Society of America Bulletin* 113(9):1133–1141
- Suski J, Rasilien K, Casanova J, Ruskeeniemi T, Blomqvist R, Smellie JA (2001) U-series disequilibria in a groundwater flow route as an indicator of uranium migration processes. *J Contam Hydrol* 47:187–196
- Thurber DL (1962) Anomalous $^{234}\text{U}/^{238}\text{U}$ in nature. *J Geophys Res* 65:4518–4523